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EFFECT OF SOUTH ATLANTIC MAGNETIC ANOMALY ON SERT II ORBITAL ACCELERATION MEASUREMENTS

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SUMMARY

Unpredicted perturbations as large as 0.1 μg in the measured SERT II spacecraft orbital acceleration are described and correlated with the South Atlantic magnetic anomaly.

INTRODUCTION

The mission of the SERT II spacecraft, orbited in February 1970, was to provide a life test of an ion thruster operating in space (ref. 1). A highly sensitive, miniature electrostatic accelerometer (MESA) was aboard SERT II to determine the thrust produced by the ion thruster. This was to be accomplished by measuring the acceleration imposed on the 1434-kilogram (3162-lb) spacecraft by the continuous 28-millinewton (6.3-mlb) thrust (ref. 2).

Acceleration measurements were obtained both before and after the ion-thruster turnon. The accelerometer data showed a marked perturbation of up to 0.1 μg whenever the SERT II spacecraft in its 1000-kilometer orbit passed over the South Atlantic in the region of the known magnetic anomaly.

This report presents the MESA-measured perturbation data, shows the data are independent of thruster operation, and correlates the occurrence of the acceleration perturbations with a map of radiation particle density at a 1000-kilometer altitude. The relation of the data perturbations to the South Atlantic magnetic anomaly is clearly illustrated. No attempt is made in this report to propose a mechanism for this effect. Study of possible effects of magnetic fields or charged particles on the MESA operation itself has failed to produce any reasonable theories relating the perturbations to accelerometer error.

SERT II SPACECRAFT AND ORBIT

The SERT II spacecraft was launched on February 3, 1970, into a nearly Sun-synchronous, nearly polar, circular orbit of about 1000-kilometer altitude. It consists of an expended Agena stage permanently affixed to the spacecraft support and experiments section. A large solar array, attached to the Agena, supplies electrical power for the ion thruster, for housekeeping, and for the other experiments.

The spacecraft is stabilized in orbit so that the Agena long axis always lies along the Earth radius line and so that the solar panels and thrusters always lie in the orbit plane. The Earth-oriented stabilization is achieved by means of gravity gradient torque coupled with control moment gyros. The desired solar panel to Sun orientation is achieved by inclining the orbit so that is precesses at the rate required (ref. 1).

There are two ion thrusters aboard, only one of which operates at any time. Each thrust vector is alined by means of gimbals to pass through the spacecraft center of mass forming a 10° angle with the spacecraft long or yaw axis. Thus, there is a component of thrust directed along the orbit radius which is proportional to the cosine of 10° and another component which is directed along the orbit tangent and is proportional to the sine of 10°. The MESA accelerometer is oriented with its sensitive axis parallel to the yaw axis so that it senses the radial component of thrust.

MESA ACCELEROMETER

The electrostatic accelerometer is a single axis instrument designed for measurement of extremely low accelerations in a low-gravity environment. State-of-the-art techniques in machining are required to produce a successful instrument based on the principle of electrostatic force. A detailed description of the basic MESA structure and operating principles is found in references 3 and 4.

Electrostatic forces are used both for the support of the acceleration sensing element (the proof mass) and for the measurement of external acceleration. The proof mass is suspended orthogonal to the accelerometer sensitive axis by means of ac voltage through series tuned inductance-capacitance circuits. The magnitude of this voltage is selected to support the proof mass against the expected level of cross-axis acceleration forces. The lower the cross-axis g environment, the lower the required cross-axis voltages. It is advantageous to reduce the support voltages as much as practical, commensurate with the expected environment, to reduce the instrument null bias. This null bias represents the instrument output with zero input acceleration. In general, the null bias term is proportional to the cross-axis support forces. The cross-axis suspension capability for the SERT II MESA was 100 μg's.

The MESA uses an electrostatic force rebalance method in the sensitive axis to measure acceleration. The frequency of voltage pulses required to maintain the proof mass at its balance point is proportional to the external acceleration. The voltage pulse amplitude, width, and maximum frequency determine the full scale sensitive axis acceleration capability of the instrument. For SERT II, the MESA full scale was set for 100 μg's even though only about 2 μg's were to be measured. This full scale was chosen as the minimum which would allow accurate calibration on Earth. Unlike most instruments, the MESA measurement error is a percentage of reading, plus null uncertainty, rather than the usual percentage of full scale, plus null uncertainty. Thus, in space 2 percent of full scale can be measured with essentially the same accuracy as 100 percent of full scale except for the null uncertainty (ref. 3). The internal data conditioning provides 100-second averages of the measured frequency. Because the MESA output is based on frequency averaging and because of large internal damping, the MESA is a steady state instrument.

The only presently practical method of on-Earth calibration of the MESA uses accurate small angle deflection and measurement to produce low magnitude input accelerations derived from Earth's g vector.

SERT II ACCELERATIONS

Figure 1 shows the SERT II spacecraft configuration details pertinent to the MESA. The MESA is located at a distance $d = 2.39 \pm 0.015$ meter from the vehicle center of mass with the sensitive axis alined with the spacecraft yaw axis, and with positive acceleration defined as acceleration toward the spacecraft center of mass. The thrust vector is $\varphi = 10^{\circ}$ from the MESA sensitive axis. Equation (1) is the expected sensitive axis acceleration at the MESA location, consisting of the thrust-produced term $F \cos \varphi$ divided by the spacecraft mass and two simplified orbital components:

$$a = \left(\frac{F \cos \varphi}{m_s} + d\omega^2 + \frac{2d\mu}{r^3}\right) \frac{1}{g} \tag{1}$$

where

a MESA sensitive axis acceleration, g's

d distance from spacecraft center of mass to MESA proof mass, m

F thrust, N

g free fall standard acceleration, 9.807 m/sec^2

m_s spacecraft mass, kg

r distance from center of Earth to spacecraft center of mass, m

μ universal gravitational constant times mass of Earth, m^3/sec^2

φ angle between MESA sensitive axis and thrust vector, deg

$\dot{\omega}$ orbital rate, rad/sec

Since the spacecraft is gravity gradient stabilized, it has a pitch rate of one revolution per orbit. The MESA thus revolves about the spacecraft center of mass at a once per orbit rate and senses a centripetal acceleration $d\omega^2$. The third term in equation (1) is the gravity gradient component which is due to the MESA being closer to the Earth than the spacecraft center of mass.

The orbital accelerations for SERT II at the MESA location were calculated to be 0.73 μg. Other sensitive axis accelerations due to vehicle attitude and accelerometer misalinement contribute terms two orders of magnitude less than these and are considered insignificant.

The expected ion thrust for SERT II was about 28 millinewtons (6.3 mlb). For $\varphi = 10^{o}$ and m_s = 1434 kilograms (3162 lb) the thrust-produced acceleration was calculated to be 1.9 μg's.

SOUTH ATLANTIC MAGNETIC ANOMALY

It is possible to represent the Earth's magnetic field as a dipole only to a rough approximation (ref. 5). The real geomagnetic field is very complex with a number of anomalies in the field strength. These magnetic anomalies are regions with weak magnetic fields as compared with the surrounding regions. The largest anomaly resides over the South Atlantic.

The weak field strength in an anomaly allows radiation belt particles to approach the Earth's surface more closely. Therefore, maps of density of energetic particles obtained from satellite data can be used to illustrate the form and location of the anomalies at different altitudes. The use of particle density maps is the technique employed in this report to correlate accelerometer data with anomaly coordinates. The satellite data used (ref. 6) were obtained from an electron scintillation spectrometer aboard the U. S. Air Force Satellite Hitch-Hiker I (1963-25B), launched on July 1, 1963. Extensive data were obtained at altitudes of about 1000 kilometers, identical to the SERT II orbital altitude.

RESULTS AND DISCUSSION

MESA acceleration data were obtained for several orbits before ion thruster turnon and for a period of several days after thruster operation was initiated. The 100-second-average acceleration measurements were plotted on a one-plot-per-orbit basis. Many of the orbital plots showed unexpected transient perturbations of the expected steady state data. These perturbations are illustrated in figure 2 for both thruster-off and thruster-on conditions. The transients were not always of the same amplitude and had a maximum acceleration change of about 0.1 μg in 500 seconds.

It was then determined that the maximum perturbations occurred with a 12-hour repetition cycle. Since the nearly polar orbit of the SERT II spacecraft followed the sunlight terminator, the spacecraft was known to pass over approximately the same area on the Earth once every 12 hours (dawn and sunset). Tabulations were then obtained of the transient amplitude, time of occurrence, and spacecraft location at the time of occurrence. The perturbation "time-of-occurrence" is defined as the time midpoint between the start of the negative slope of the transient and the leveling off of the transient, as illustrated in figure 2 by the arrow. The repeatability of this determination was about ± 100 seconds, the time resolution of the MESA data.

The perturbation magnitudes are categorized in four groups of 0.10 to 0.12 μg, 0.08 to 0.09 μg, 0.06 to 0.07 μg, and 0.02 to 0.05 μg (0.02 μg is the smallest discernible transient) and the groups are labeled 1 to 4, respectively.

Figure 3 is a map of the spacecraft location at time of occurrence for the transient data superimposed on a map of energetic electrons (ref. 6) measured at an altitude of 1000 kilometers. The maximum magnitude perturbations closely correlate with the center of the South Atlantic anomaly. The remaining groups are progressively farther removed from the anomaly center as the magnitude decreases. All transient data obtained from the SERT II MESA are shown in figure 3.

The geographic correlation of the MESA acceleration data perturbations with the South Atlantic anomaly is definite. The mechanism by which the spacecraft acceleration is produced is unknown at this time. Whether the MESA accelerometer measured a real spacecraft acceleration can be questioned, but no mechanism by which the accelerometer readings can be erroneously affected by a magnetic or radiation anomaly has as yet been proposed. The authors assume that the acceleration perturbations are real and feel that their existence might be of interest to future spacecraft designers and experimenters.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 17, 1970,
720-03.

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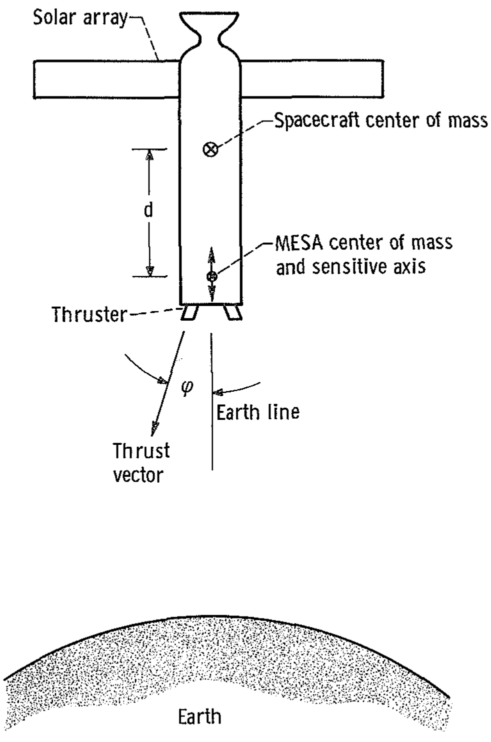

Figure 1. - SERT II acceleration measurement configuration.

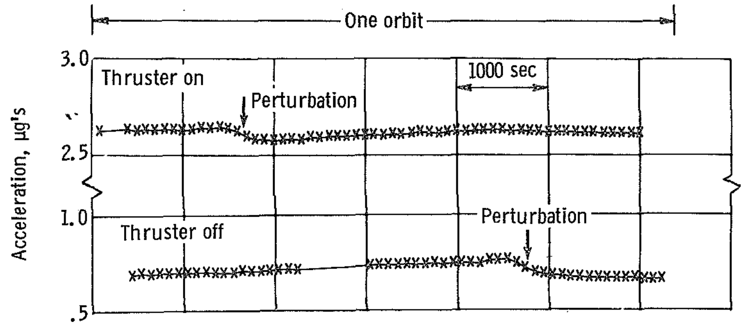

Figure 2. - MESA acceleration data.

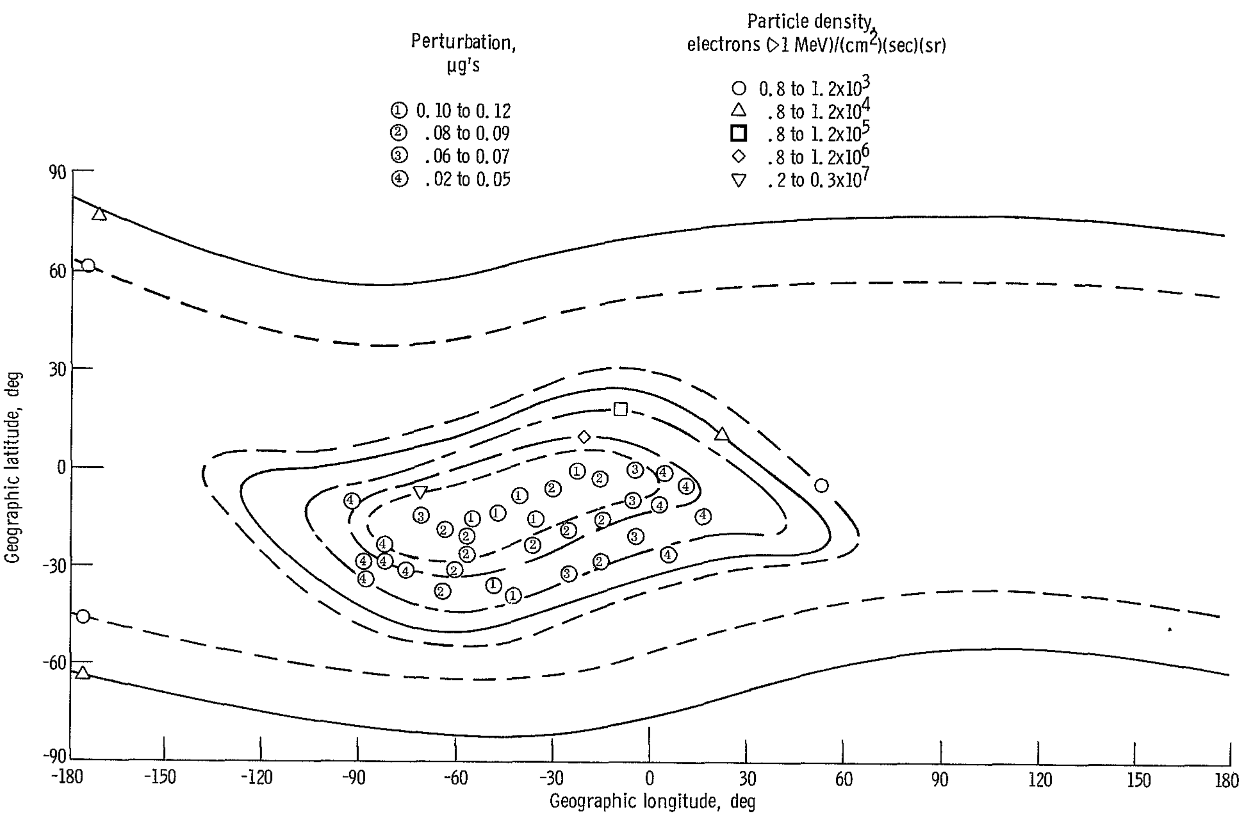

Figure 3. - Correlation of SERT II MESA data perturbations with South Atlantic magnetic anomaly. Altitude, 1000 kilometers.

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